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REDUCTION OF THE TENSILE STRESS STATE IN LASER TREATED MATERIALS

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Introduction

It is well known that by laser melting the wear performance of metals can be improved [1]. After laser treatment the surface may consist of a dendritic structure consisting of tiny cells (order of μm). Carbide particles may also become homogeneously dispersed. Despite these advantages, the laser treatment often results in a tensile stress in the surface layer which in the case of RCC steel (2.05 wt.% C, 11.05 wt.% Cr, 0.62 wt.% W, and the balance, Fe), can be so severe that spontaneous cracking occurs.

In conformity with conventional welding technologies [2], during a laser treatment residual stresses are being detected [3,4,5].Beside volume changes due to local phase transformations, residual stresses are the consequence of a nonuniform plastic flow during the laser treatment. During the laser treatment the material will become melted and outside the laser track a heat affected zone exists, where plastic deformation takes place. Upon cooling, the track will resolidify starting at the solid/liquid interface towards the centre of the track by heat conduction and a thin surface layer on top by radiation. The shrinkage taking place during cooling causes tensile stresses to develop which when exceeding the yield stress will produce plastic deformation. The heat affected zone remains solid but the compressive stresses during heating will be high enough to produce plastic deformation [6].

In this work a novel method is presented which inverts the tensile stress while maintaining the advantages of the laser treatment. In previous work [7], implantation of a noble gas was used as a remedy against the residual tensile stresses. Here shot peening is introduced that has several advantages over implantation: the influenced layer is thicker (75 μm compared to 0.1 μm), and the technique is more effective since shot peening results in a compressive residual stress state whereas implantation only reduces the tensile stress. Finally, shot peening is easily applicable on an industrial scale.

Experiments

In this study we used a transverse flow Spectra Physics 820 CO_2 laser of 1.5 kW, with its beam focussed using a 127 mm ZnSe lens. The sample is mounted on a numerically controlled X-Y table. Argon was used as a shielding gas to prevent oxidation. The conditions were 1300 W power on the surface, focus point 15 mm above the surface, and a scan velocity of 4 cm/s. This results in laser weld tracks with a width of 2 mm and an average depth of 0.15 mm. Melted tracks were made adjacent to each other at a distance of 1 mm apart.

After laser treatment shot peening was carried out using glass beads with a diameter of 700 μm which were shot during 5 min at the metal surface using air at a pressure of 3 bar. Regular filtering of the shot material was done to remove broken glass beads.

The stress measurements were carried out using a well-aligned Philips X-ray diffraction system (PW1830 equipped with a θ drive). The diffractometer is equipped with a fine focus copper tube operated at 50 kV, 20

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mA and a graphite monochromator in the diffracted beam which filtered all radiation except $K\alpha$. Copper radiation was chosen because of the small penetration depth. (Penetration depth at 90% intensity loss, Cu on steel: 5 μm, Cr on steel 10 μm). This is especially important for stress measurements of implanted steels (the implantation depth of 100 keV Ne^+ ions in steel is approx. 0.1 μm), but also in cases where stress gradients perpendicular to the surface are expected.

Wear experiments were carried out using a conventional pin on disk apparatus using a ruby ball with a diameter of 5 mm. The disk is made of the material under investigation. For the wear experiment the samples were slightly polished with SiC paper and diamond paste. In order to prevent oxidation the instrument is placed in a nitrogen ambient. The effect of humidity is reduced by applying absolute ethanol. The wear volume was measured using an interference microscope to determine the profile of the wear track.

Layer removal was carried out by chemical polishing (85 v.% acetic acid, 5 v.% H_2O, 10 v.% perchloric acid). The removed layer thickness was determined by weighing the sample before and after polishing. The advantage of this method of layer removal over mechanical methods is that no new stress components are introduced. A disadvantage, however, is that the determination of the removed layer thickness becomes less accurate since after several polishing passes, some preferential etching/polishing takes place.

The samples are cut from steel rods with a diameter of 38 mm. The thickness of the samples is 5 mm, thick enough to ensure enough bulk material for the heat flow during the laser treatment. Before the samples were laser treated they were sand blasted to obtain a surface which absorbs well the laser light (wavelength 10.6 μm) and cleaned ultrasonically in ethanol and freon. Next, after the laser treatment, the samples were cleaned again followed either by implantation or shot peening. Prior to the wear experiment the samples were slightly polished. For the stress measurement no subsequent sample treatment was necessary. The samples were flat within 0.1 mm, even after the laser treatment.

Results

The stress σ_ϕ is measured using the $\sin^2\psi$ method [8]:

$$\varepsilon_{\psi\phi} = \frac{d_{\psi\phi} - d_0}{d_0} = \frac{(1-\nu)}{E}\sigma_\phi \sin^2\psi,$$

where E represents the modulus, ν Poissons ratio, d_0 the strain free [hkl] plane distance, $d_{\psi\phi}$ the strained [hkl] plane distance, ε the strain and σ_ϕ the stress to be determined.

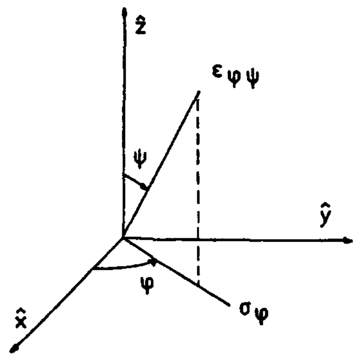

Fig. 1 Definition of directions ψ and ϕ.

For ψ and ϕ reference is made to fig. 1. The stresses normal to the surface are assumed to be zero. E=220 GPa and $\nu = 0.3$ were used for the stress analysis.

Line profiles of the {420} diffraction peak ($2\theta \approx 143°$) were measured at six equidistant $\sin^2\psi$ values from 0 to 0.5. Both positive and negative values of the ψ angle were used for the measurements but only peak positions of the positive ψ angles were used for the stress analysis. The use of negative ψ angles can be informative as the penetration depth varies with ψ angle giving the smallest perpendicular penetration for the negative ψ angles.

In this case the deviation of the negative branch in the ε versus $\sin^2\psi$ plot is small which indicates a homogeneous stress situation within the 5 μm layer.

The stress in the shot peened RCC sample turned out to be 1200 MPa (fig. 2), large enough to produce cracks in the surface ground using SiC paper. Subsequent shot peening prevented cracking. The stress measured was -900 MPa (fig. 2). Layer removal (fig. 3) revealed an increase in compressive stress in the first few μm and at a depth of 5 to 70 μm a nearly constant value of -1200 MPa. Below 70 μm the stress increases to zero indicating the end of the zone affected by shot peening. Although the values of stress deeper then 70 μm are not correct due to the effect of layer removal on the general stress state, the values ranging from 5 to 70 μm are correct due to the lack of strong gradients. Therefore, no correction for layer removal has been performed.

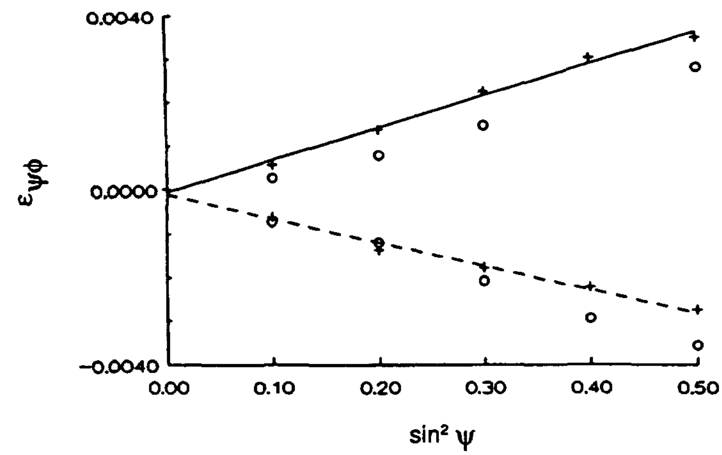

Fig. 2 $\varepsilon_{\psi\phi}$ vs. $\sin^2\psi$ after laser treatment (solid line) and after subsequent shot peening (dashed line).

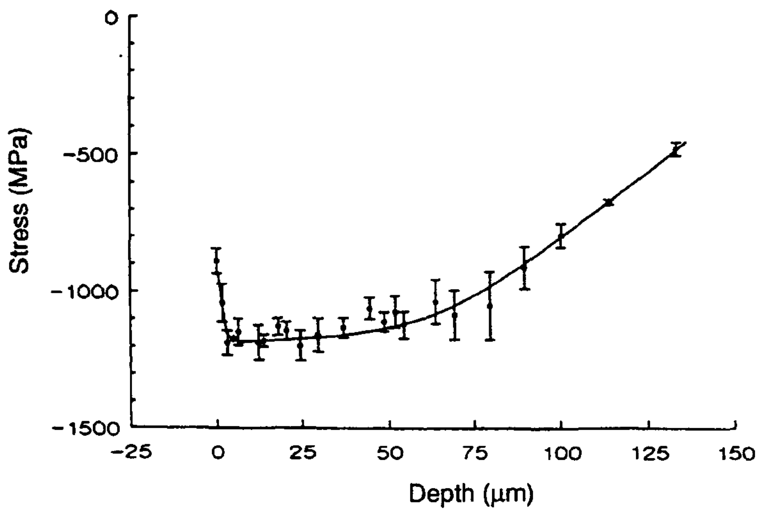

Fig. 3 Stress as a function of depth.

The wear experiment was performed on a sample that was fully laser treated, but only half peened. In this way environmental differences are totally excluded. On the other hand, one must be aware of the possibility that the wear mechanism of the not peened half is influenced by the peened half, or vice versa. Additional experiments lead us to the conclusion that this is not the case. The wear volumes as a function of the number of turns, as measured with an interference microscope, are depicted in figure 4. It is clearly visible that both the steady-state wear and the running-in wear have decreased by roughly a factor two. This is caused by a higher hardness, a changed microstructure and a different stress state.

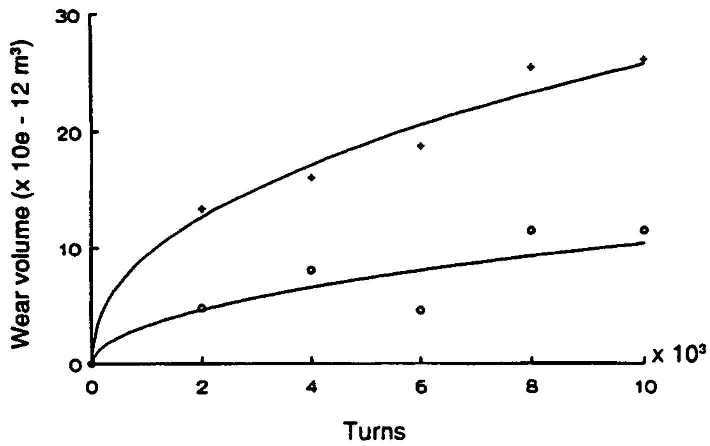

Fig. 4 Measured wear volume of laser melted RCC steel: + not peened, o peened.

Hardness measurements are performed on a cross section of the laser treated/shot peened surface. Because the hardness varies strongly with depth, one should keep the dimension of the indention in that direction small. Therefore it is best to use a Knoop indenter. To get a hardness value just below the surface the specimen was investigated not cross sectionally but plane-parallel. From figure 5 it is clear that the penetration depth of peening treatment is approximately 70 µm which is in accordance with the X-ray stress measurements. This is in the same order of magnitude as the laser track. The increased hardness at 125 µm is caused by the martensitic phase in the heat-affected zone.

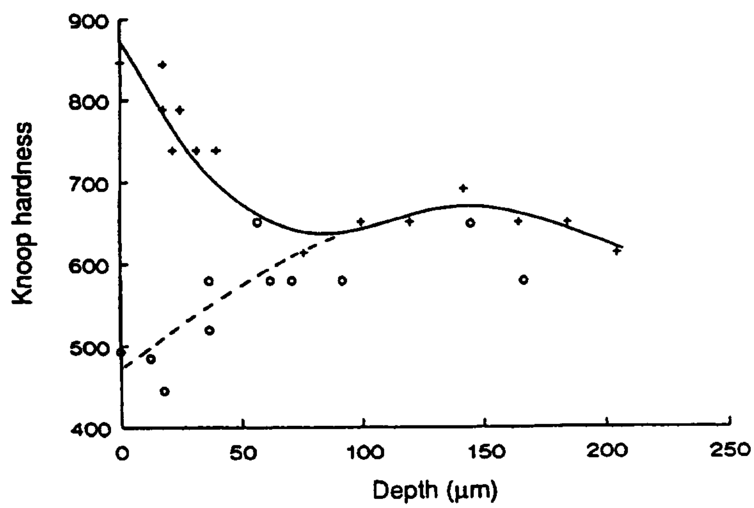

Fig. 5 Knoop microhardness as a function of depth below the surface. + not peened, o peened.

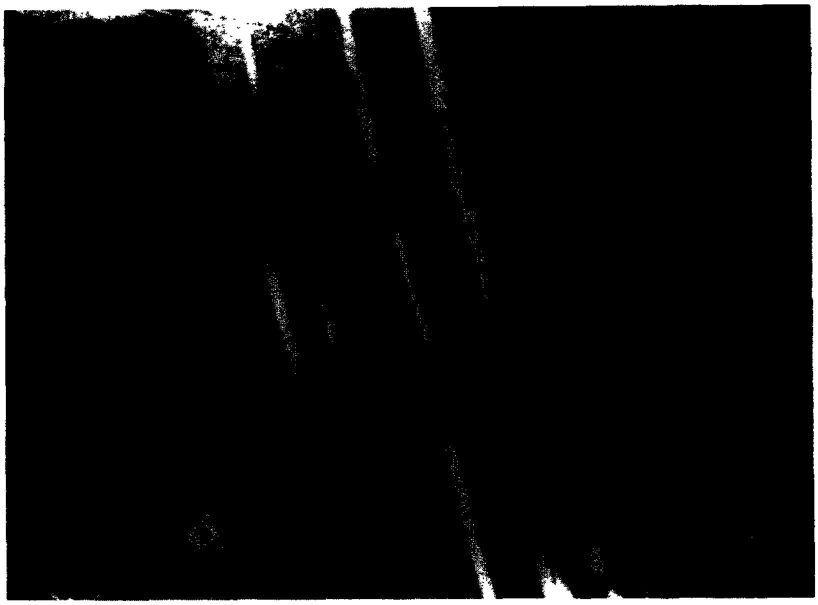

Fig. 6 Darkfield TEM micrograph, showing stress induced α-martensite in austenitic cells.

The microstructure has been examined with TEM. Specimens are prepared using a dimpler followed by ion milling in such a way that various depths below the surface can be inspected (fig. 6). At depths at least up to 15 μm, stress induced martensite is found with the same morphology as observed in a worn laser treated RCC sample [1]. At a depth of 30 μm only an increase in dislocation density was found: more than $10^{14}/m^2$ after peening compared to about $10^{13}/m^2$ before.

Conclusion

The benefit of laser treated steel can be further enhanced by a simple technique like shot peening. The wear rate decreases substantially and surface cracking does not occur. Given the experimental conditions the enhancement is such that no tensile stress is left after shot peening and that the layer under compression is thick enough for further machining.

Acknowledgements

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